Phenomenology of transverse-spin and transverse-momentum effects in hard processes

Vincenzo Barone

Di.S.T.A., Università del Piemonte Orientale 'A. Avogadro'
and INFN, Gruppo Collegato di Alessandria, 15121 Alessandria, Italy

Abstract. Some recent analyses of single-spin and azimuthal asymmetries in SIDIS and Drell-Yan processes, focusing in particular on Collins, Sivers and Boer-Mulders effects, are briefly reviewed. The perspectives for future phenomenological studies are also outlined.

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INTRODUCTION

Transverse spin and transverse momentum of quarks and/or hadrons correlate with each other in various ways, giving rise to a number of transverse-momentum dependent distributions (TMD's), some of which are leading-twist quantities. TMD's manifest themselves in single-spin and azimuthal asymmetries in partially inclusive hard processes [1]. In the last decade, semiinclusive deep inelastic scattering (SIDIS) experiments (HERMES, COMPASS, CLAS) have investigated these observables and shown that they are non vanishing and relatively sizable.

STATE OF THE ART

Most of the phenomenological work focuses on three distributions functions: the transversity distribution $h_1(x)$, the Boer-Mulders function $h_1^{\perp}(x, k_T^2)$ (spin asymmetry of transversely polarized quarks inside an unpolarized target) and the Sivers function $f_{1T}^{\perp}(x, k_T^2)$ (azimuthal asymmetry of unpolarized quarks inside a transversely polarized nucleon). The first two combine in SIDIS with the Collins fragmentation function $H_1^{\perp}$, which describes the fragmentation of transversely polarized quarks into an unpolarized hadron. The processes considered by present phenomenological analyses are: $e\,p^{\uparrow} \to e'\,\pi\,X$ (Collins and Sivers effects with different angular distributions), $e\,p \to e'\,\pi\,X$, $p\,p \to \mu^+\,\mu^-\,X$ (Boer-Mulders effect), $e^+\,e^- \to \pi\,\pi\,X$ (Collins effect).

The parton-model expressions of the SIDIS structure functions involving the three TMD's mentioned above are

$$\text{Collins} \qquad F_{UT}^{\sin(\phi_h+\phi_S)} = \mathscr{C}\left[-\frac{\hat{h}\cdot\vec{\kappa}_T}{M_h}\,h_1 H_1^{\perp}\right] \tag{1}$$

$$\text{Sivers} \qquad F_{UT,T}^{\sin(\phi_h-\phi_S)} = \mathscr{C}\left[-\frac{\hat{h}\cdot\vec{k}_T}{M}\, f_{1T}^{\perp} D_1\right] \tag{2}$$

$$\text{Boer-Mulders} \qquad F_{UU}^{\cos 2\phi_h} = \mathscr{C}\left[-\frac{2(\hat{h}\cdot\vec{k}_T)(\hat{h}\cdot\vec{\kappa}_T)-\vec{k}_T\cdot\vec{\kappa}_T}{MM_h}\, h_1^{\perp} H_1^{\perp}\right] \tag{3}$$

where $\vec{k}_T$ ($\vec{\kappa}_T$) is the transverse momentum of the incoming (fragmenting) quark, the apices indicate the azimuthal modulation (ϕ_h and ϕ_S being the azimuthal angles of the final hadron and of the target spin, respectively) and $\mathscr{C}$ is a convolution in the transverse momentum space.

TMD's are usually written as factorized functions of x and k_T, and their transverse-momentum dependence is often assumed to have a Gaussian form. A typical parametrization for the Sivers and the Boer-Mulders functions is

$$f_{1T}^{\perp}(x,k_T^2),\; h_1^{\perp}(x,k_T^2) \sim x^{\alpha}(1-x)^{\beta}\, \mathrm{e}^{-k_T^2/\langle k_T^2\rangle}\, f_1(x)\,, \tag{4}$$

where $f_1(x)$ is the ordinary number density. Due to the kinematics of current experiments and to the structure of SIDIS observables, high-x tails and antiquark distributions are at present largely unconstrained.

A combined analysis of the SIDIS data on the Collins asymmetry from HERMES and COMPASS, and of the e^+e^- Belle data, was performed by Anselmino et al. [2, 3] and led to the first extraction of the u and d transversity distributions, which turned out to have opposite signs, with $|h_1^d|$ smaller than $|h_1^u|$.

The Sivers asymmetry has been measured by HERMES and COMPASS and phenomenologically studied in [4] and in [5]. The resulting Sivers functions for u and d have comparable magnitudes and opposite signs ($f_{1T}^{\perp u} < 0$, $f_{1T}^{\perp d} > 0$).

The $\cos 2\phi_h$ asymmetry in unpolarized SIDIS at small transverse momentum provides information on the Boer-Mulders function. In [6] it was predicted that the π^- asymmetry should be larger than the π^+ asymmetry, as a consequence of the Boer-Mulders effect. This prediction has been substantially confirmed by the experimental results. A fit to the HERMES [7] and COMPASS [8] preliminary data has been performed in [9]. It assumes that $A_{UU}^{\cos 2\phi_h}$ can be described by the leading-twist Boer-Mulders component and by the so-called Cahn term [10]

$$F_{UU,\mathrm{Cahn}}^{\cos 2\phi_h} = \frac{M^2}{Q^2}\,\mathscr{C}\left[\frac{(2(\hat{h}\cdot\vec{k}_T)^2-k_T^2)}{M^2}\, f_1 D_1\right] \tag{5}$$

which is however only part of the full twist-4 contribution, still unknown. As the available data do not allow a complete determination of the x and k_T dependence of $h_1^{\perp}$, the Boer-Mulders functions are simply taken to be proportional to the Sivers functions of [4], $h_1^{\perp q} = \lambda_q f_{1T}^{\perp q}$, and the parameters λ_q are obtained from the fit. The result, $h_1^{\perp u} \simeq 2\, f_{1T}^{\perp u}$, $h_1^{\perp d} \simeq -\, f_{1T}^{\perp d}$, is consistent with expectations from the impact-parameter picture and lattice QCD. The comparison with the data is shown in Fig. 1.

The $\cos 2\phi$ asymmetry has been measured also in unpolarized Drell-Yan (DY) production, where it is represented by the so-called ν parameter. At small Q_T this quantity

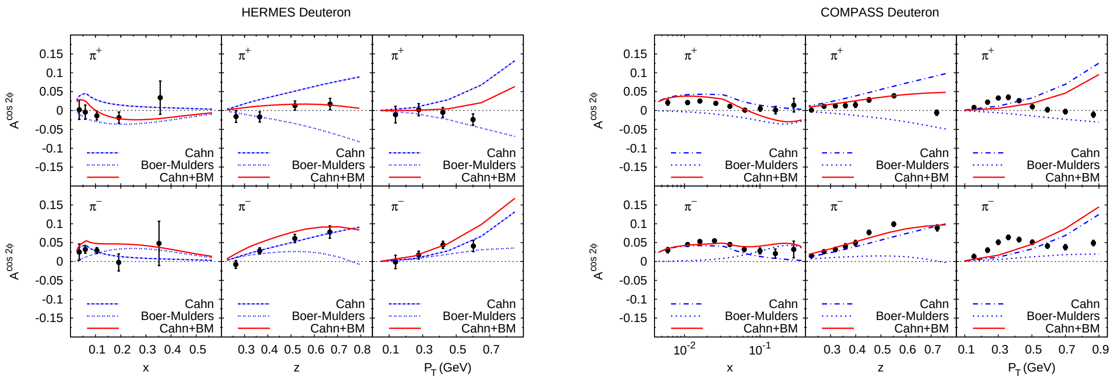

FIGURE 1. The preliminary results for the $\cos 2\phi$ spin-independent azimuthal asymmetries for deuteron from HERMES [7] (left) and COMPASS [8] (right) as functions of x, z and $P_{h\perp}$ compared with the fit of [9].

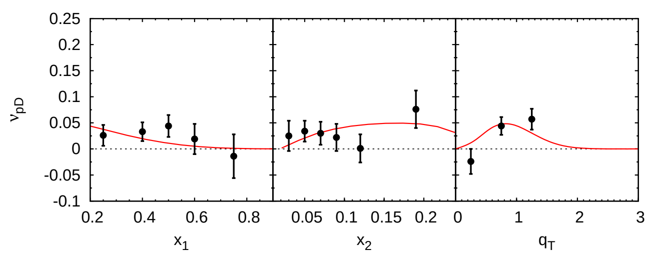

FIGURE 2. The ν parameter in pD Drell-Yan production: the fit of [13] vs. the E866/NuSea data [11].

is dominated by the Boer-Mulders contribution and is given by

$$\nu = \frac{2\,W_{UU}^{\cos 2\phi}}{W_{UU}^{1} + W_{UU}^{2}}\,, \qquad W_{UU}^{\cos 2\phi} = \frac{1}{3}\,\mathscr{C}\left[\frac{2(\hat{h}\cdot\vec{k}_{1T})(\hat{h}\cdot\vec{k}_{2T}) - \vec{k}_{1T}\cdot\vec{k}_{2T}}{M_1 M_2}\, h_1^{\perp}\bar{h}_1^{\perp}\right]. \tag{6}$$

The E866/NuSea Collaboration at FNAL has presented results for the ν asymmetry in pD [11] and pp [12] collisions, from which one can get some information on the antiquark Boer-Mulders distributions. The analysis of the SIDIS $\cos 2\phi$ distribution has been extended to the corresponding DY observable in [13]. The quality of the fit is shown in Fig. 2. The combined SIDIS and DY analysis allows determining both the magnitude and the sign of the quark and antiquark distributions.

PERSPECTIVES

In spite of its important achievements, the phenomenology of TMD's is still in its infancy. The mature stage will be represented by truly global analyses. These should: *i)* incorporate the exact evolution of TMD's; *ii)* take all perturbative and non-perturbative effects into account and fit simultaneously polarized and unpolarized cross sections; *iii)*

use datasets with larger statistics and wider kinematics. More SIDIS data are expected from JLab and from future facilities (EIC), but in the short-to-medium term the main improvement will come from polarized DY measurements: COMPASS ($\pi^{\pm} p^{\uparrow}$), PANDA ($\bar{p}p^{\uparrow}$), PAX ($\bar{p}^{\uparrow} p^{\uparrow}$), J-PARC, NICA, RHIC ($p^{\uparrow}p$). A list of DY observables is (ϕ is the azimuthal angle of dileptons in the Collins-Soper frame)

- $\pi^{\pm} p$: $\quad \bar{h}_1^{\perp \pi} \otimes h_1^{\perp p} \; \cos 2\phi$
  Driven by valence. Expected to be large (10-15%), but involves the Boer-Mulders function of the pion.
- $\pi^{\pm} p^{\uparrow}$: $\quad \bar{f}_1^{\pi} \otimes f_{1T}^{\perp p} \; \sin(\phi - \phi_S) + \bar{h}_1^{\perp \pi} \otimes h_1^{p} \; \sin(\phi + \phi_S)$
  Driven by valence. The $\sin(\phi - \phi_S)$ asymmetry probes the Sivers function of the proton (the unpolarized distribution of the pion is fairly well known).
- pp : $\quad \bar{h}_1^{\perp p} \otimes h_1^{\perp p} \; \cos 2\phi$
  Involves the sea. Known to be small (few percent).
- $pp^{\uparrow}$: $\quad \bar{f}_1^{p} \otimes f_{1T}^{\perp p} \; \sin(\phi - \phi_S) + \bar{h}_1^{\perp p} \otimes h_1^{p} \; \sin(\phi + \phi_S)$
  Involves the sea, but is useful to extract the Sivers function.
- $\bar{p}p$: $\quad h_1^{\perp p} \otimes h_1^{\perp p} \; \cos 2\phi$
  Driven by valence. Expected to be large. Ideal to extract the Boer-Mulders function.
- $\bar{p}p^{\uparrow}$: $\quad f_1^{p} \otimes f_{1T}^{\perp p} \; \sin(\phi - \phi_S) + h_1^{\perp p} \otimes h_1^{p} \; \sin(\phi + \phi_S)$
  Driven by valence. The $\sin(\phi - \phi_S)$ asymmetry ideal to extract the Sivers function.
- $\bar{p}^{\uparrow} p^{\uparrow}$: $\quad h_1^{p} \otimes h_1^{p} \cos(2\phi - \phi_{S_1} - \phi_{S_2})$
  Driven by valence. Ideal to extract the transversity.

As one can see, polarized DY processes probe various combinations of TMD's and promise to become a fundamental ingredient of future phenomenological analyses.

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